MOLECULAR HYDROGEN IN THE GALAXY AND GALACTIC GAMMA RAYS

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Estimates made of column densities of H_2 at $\ell^{II} = 0^o$ indicate that H_2 is far more abundant than HI in the inner galaxy and is the key to an explanation of the γ-ray observations. This is also reflected in the correlation of galactic longitude and latitude distributions of γ-rays and molecular clouds. Particularly strong evidence is found from the galactic survey of CO emission at 2.64 mm. The cosmic-ray distribution inferred from the calculations is not uniform but only weakly dependent on the total gas distribution in the inner galaxy.

1. Introduction. Molecular hydrogen has long been suspected to be an important component of interstellar gas because it is the most stable low-temperature form of the most abundant element in the galaxy. H_2 is expected to be the predominant form of hydrogen in cool clouds of sufficient density. However, despite its abundance, it is difficult to measure its galactic distribution directly. Results from two promising methods for indirectly studying the galactic distribution of H_2 are discussed here, viz., recent galactic surveys of 100 MeV γ-radiation and 2.6 mm radio line emission from the $J = 1 \rightarrow 0$ transition of CO molecules. To these surveys, which reflect the extent and distribution of H_2 in the plane of galaxy, we will add corroborating information on the amount and latitude distribution of gas in the direction of the galactic center supplied by X-ray, optical, and infrared absorption measurements.

2. The Recent SAS-2 Gamma-Ray Galactic Longitude Observations. Fichtel et al. (1975) have recently reported the results of a sky survey made of 100 MeV γ-rays using a spark chamber aboard the SAS-2 satellite. The similar galactic longitude distribution observed by the OSO-3 detector was also noted to be distinctly uncorrelated with the 21 cm distribution by Clark et al. (1970). The OSO-3 result implied an increase in cosmic-rays, unseen gas or both in the inner galaxy, and it was suggested by Stecker (1969, 1971) and Stecher and Stecker (1970) that molecular

*NAS/NRC Postdoctoral Resident Research Associate. Permanent Address: Centre d'Etudes Nucleaires de Saclay, 91190 Gif-sur-Yvette, France hydrogen unseen in 21 cm surveys could account for a large part of the γ-ray enhancement in the inner galaxy. A model has been proposed by Bignami and Fichtel (1974) and Bignami et al. (1975) based on producing large enhancements at the locations of arms mapped by 21 cm surveys by postulating higher gas densities than are seen in 21 cm and proportionately higher cosmic-ray intensities in the arms. However, Burton et al. (1975) indicate that the arms outside of 25^o from the galactic center are optically thin in 21 cm and significantly higher amounts of HI in the arms than those deduced in previous surveys appear to be ruled out. We, therefore, feel that the galactic γ-ray observations can be better understood by using other observations in addition to 21 cm surveys to determine the role of H_2 clouds invisible in 21 cm emission.

3. The Galactic CO Distribution and the Molecular Ring at ∿5kpc. A survey of the galactic longitude distribution of CO emission in the galactic plane has recently been made by Scoville and Solomon (1975). The importance of this survey in understanding the distribution of H_2 in the galaxy lies in the fact that CO is an excellent tracer of H_2.

Scoville and Solomon (1975) have used the velocity profile data obtained in their CO survey in conjunction with the Schmidt (1965) rotational model of the galaxy to determine the mean distribution of CO in the galaxy as a function of galactocentric distance for distances greater than 2.6 kpc. This distribution shows a broad peak with a maximum near 5 kpc which they have concluded indicates a ring of H_2 clouds in this region. The general form of the molecular cloud distribution obtained by Scoville and Solomon has recently been confirmed in an independent CO survey by Burton et al. (1975). The connection between this feature and the γ-ray emission ring at ∿5 kpc (Puget and Stecker, 1974) led to the suggestion that the γ-ray data also provide evidence for the molecular cloud ring near 5 kpc (Solomon and Stecker, 1974). Coincidently, there is also a similar distribution and peak in the giant HII regions of the galaxy (Metzger 1970). This may be understood to be the effect of hot young stars in OB associations being formed out of dense molecular clouds in this ring. The formation of such a prominent molecular ring poses an intriguing problem for galactic structure theory.

4. Molecular Hydrogen and Total Column Densities in the Direction $\ell=0^o$. Various methods can be used to estimate the amount of gas in the direction of the galactic center (Stecker et al. 1975). The results are summarized in Table 1.

Table 1. Column Densities of Hydrogen at $\ell = 0^o$ Excluding the Galactic Nucleus ($\times 10^{-22}$) (cm^{-2}) ($N_{G.C.,\odot}$)

$\langle N_{HI} \rangle$ from 21 cm radio	$\gtrsim 0.6$ to 1.5	Daltabuit and Meyer (1972)
	1 to 2	Kerr and Westerhout (1965)
	$\gtrsim 1.2$	Clark (1965)
$\langle 2N_{H_2} \rangle$ from CO	3 to 10	Scoville and Solomon (1975)
$\langle 2N_{H_2} + N_{HI} \rangle$ from SAS-2 γ-ray flux	$\lesssim (11.5 \pm 2)$	This work ($I_{CR} \gtrsim I_\odot$)
$\langle 2N_{H_2} + N_{HI} \rangle$ from X-ray absorption	6.5 to 9	$\sigma_{H_2}/2\sigma_{HI} \lesssim 1.7$ (Kaplan and Markin 1973) as verified by the measurements of Crasemann et al. (1974).
$\langle 2N_{H_2} + N_{HI} \rangle$ from IR absorption	5 to 7.5	Ryter, et al. (1975)

Scoville, Solomon and Jefferts (1974) estimate the total mass of the molecular disk near the galactic center to be

$$4 \times 10^7 \lesssim (M_{GC}/M_\odot) \lesssim 10^8$$

This yields an estimated flux from π^o decay in the range

$$0.6\times10^{-5} \lesssim \Delta I_{\gamma,GC} \lesssim 1.5\times10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{rad}^{-1}$$

which is only about one tenth of the observed flux at $\ell=0^o$.

5. Galactic Gamma Ray Flux as a Function of Longitude. In performing numerical calculations of the longitude distribution of the galactic γ-ray flux from π^o decay, we have used the survey of Scoville and Solomon (1975) to obtain the relative distribution of molecular hydrogen in the galaxy as a function of galactocentric distance $\tilde{\omega}$ and have normalized to a total column density of 7×10^{22} cm^{-2} in the direction of the galactic center using the X-ray and infrared absorption measurements (Table 1) which are consistent with, but presumably more accurate than the column densities deduced from the γ-ray or CO results. The contribution from atomic hydrogen was estimated based on the numbers given by Kerr and Westerhout (1965) and Westerhout (1970).

For the purpose of the calculations to estimate the effect of cosmic ray enhancements in the galaxy, it was assumed that such enhancements may be correlated with the gas distribution so that

$$\frac{J(\tilde{\omega})}{J_\odot} = \left[\frac{n_{HI}(\tilde{\omega}) + n_{H_2}(\tilde{\omega})}{n_{HI,\odot} + n_{H_2,\odot}}\right]^\alpha \tag{7}$$

The results are shown in Figure 1 for $N_{GC,\odot} = 7 \times 10^{22}$cm^{-2} and $\alpha=0.3$ corresponding to an increase of about a factor of 2 in the cosmic ray flux in the 5kpc region as indicated by studies of the supernova remnant distribution in the galaxy (Ilovaisky and Lequeux 1972, Kodaira 1974) and the synchrotron radiation measurements (Daniel and Stephens 1975). This corresponds to a mean value for the total gas density of ~1 atom/cm^3 at 10 kpc of which ~40 percent is in molecular form. This agrees with the values given by Spitzer, et al. (1973) from measurements of rotational UV absorption lines of H_2 and those given by Jenkins and Savage (1974) for Lyman α lines of HI. In the 5 kpc region, this corresponds to a volume-averaged total density of ~5 atoms/cm^3 of which ~80 percent would be in molecular form.

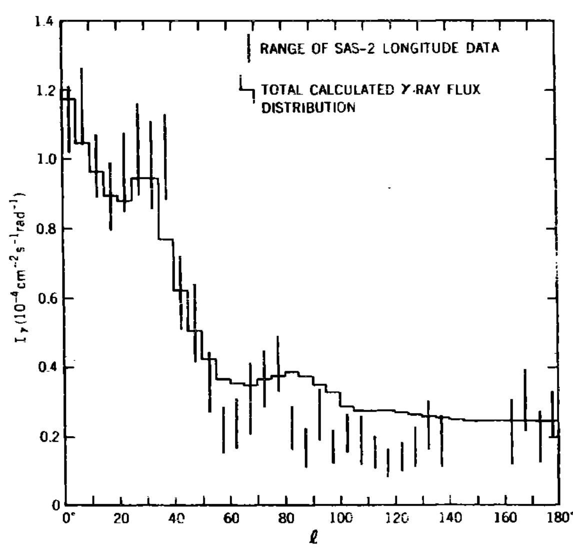

Figure 1. Comparison of the total calculated γ-ray flux distribution with the SAS-2 longitude data.

The results of the numerical calculations are shown in Figure 1 together with the flux distribution given by Fichtel et al. (1975) from the SAS-2 observations for the half-plane from 0^{o} to 180^{o} over which the CO measurements of Scoville and Solomon (1975) can be applied. Effects of secondary electron production, bremsstrahlung and Compton interactions are included. These results indicate that most of the observed γ-ray enhancement at low longitudes is primarily a result of increased gas density and that the molecular ring near 5 kpc plays an important role in accounting for this increase.

Cosmic rays are limited to a small variation over the galactic disk given by $0.2 \lesssim \alpha \lesssim 0.5$ as derived from the limits on the amount and distribution of gas implied by the observations discussed in section 4. We thus conclude that cosmic rays cannot vary linearly with gas density over all segments of the galaxy nor do they appear to be uniformly distributed.

The results indicate that the character of the longitude distribution of galactic γ-radiation corresponds well with the overall density distribution in the galaxy implied by the CO and 21 cm measurements and that this distribution has a broad maximum in the 5 to 6 kpc region. Higher frequency modulations by spiral arms do not appear to us to play a significant role in determining the galactic γ-ray ditribution within the statistical errors and 5^{o} resolution of the SAS-2 data, at least for the half plane analyzed here using the CO data. In the other half plane, $180^{o} \leq \ell \leq 360^{o}$, three apparently sharp features have been identified by Fichtel et al. (1975) with the Scutum, Norma and "3 kpc" arm features designated in 21 cm surveys. The two inner features at 330^{o}-335^{o} and 340^{o}-345^{o} may correspond to a bifurcation of the broad moleuclar ring near 5 kpc on the other half-plane of the galaxy; the feature at 310^{o}-315^{o} is perhaps somewhat more puzzling since this should be associated with a correspondingly strong feature at $\ell \simeq 50^{o}$ which appears to be absent in both the γ-ray and CO data. There are, however, large error bars associated with the 310^{o}-315^{o} observation due to the fact that the SAS-2 spark-chamber telescope only viewed this direction obliquely. Also, Puget et al. (in prep.) have indicated that large corrections due to nearby features are necessary in the 310^{o}-360^{o} region. Future CO observations from the southern hemisphere could help increase our understanding of the matter distribution in this region.

Thus, the galactic gas seems to have a large-scale superstructure modulated by spiral arm perturbations similar to that seen in M31 in 21 cm emission (Guibert 1974, Emerson 1974) and in our own galaxy in nonthermal radio emission (Price 1974) and it appears to be this superstructure which determines the character of the general central enhancement in the γ-ray longitude distribution.

Thus, it would appear that in both external galaxies and our own Galaxy, the density gradient of the H_2 distribution is steeper than that of the HI distribution, resulting in a decrease in the ratio n_{H_2}/n_{HI} with distance outward from the region of maximum density.

The total contribution from bremsstrahlung and Compton interactions of both primary and secondary electrons to the galactic γ-ray flux in the central region is of the order of 30 percent, in agreement with the estimates made by Stecker et al. (1974) using the observed γ-ray energy spectrum obtained by SAS-2.

6. Gamma-Ray Latitude Distribution and Associated Line of Sight Reddening. In addition to the γ-ray longitude distribution measurements reported by Fichtel et al. (1975), a galactic latitude distribution was also obtained. This distribution shows an asymmetry with respect to the galactic plane with more flux coming from positive galactic latitudes in the case of moderate latitudes $6^o \leq |b| \leq 30^o$. This can be understood in the context of section 4 where it was pointed out that UV, X-ray infrared absorption measurements indicate that the total column density of gas is proportional to the reddening in a given direction and that in the direction of highly reddened objects most of the hydrogen may well be in molecular form as expected in dense dust clouds and as is indicated by only a partial correlation with 21 cm emission. The data of Knapp and Kerr (1974) in the region of the sky located between $\ell = 345^o$ and 30^o and between $b = 10^o$ and 30^o can be used to evaluate the average reddening and HI column density at $b = 20^o$. We obtain $\langle E_{B-V}(20^o)\rangle = 0.26$ mag and $\langle N_H(20^o)\rangle = 9.7 \times 10^{20}$ H atoms cm^{-2}. Postulating the same cosmic ray density as observed locally we find from the reddening and relation (2) a gamma-ray flux of 2.2×10^{-5} cm^{-2} s^{-1} sr^{-1} which compares favorably with the flux reported by Fichtel et al. (1975) observed at $b = 20^o$ of 2 to $2.5 \times 10^{-5} \times 10^{-5}$ cm^{-2} s^{-1} sr^{-1}. However, the flux estimated from the HI-column density is only 1.4×10^{-5} cm^{-2} sec^{-1} sr^{-1} which is particularly significant in this case because at high galactic latitudes the 21 cm emission line is not optically thick (Knapp and Kerr 1974). Thus, the situation with regard to the latitude distribution of galactic gamma-rays is analogous to that of the longitude distribution and can be better understood by taking account of H_2 unseen in 21 cm surveys of HI gas.

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